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Experimental Study of Motion of Nitrogen Taylor Bubbles and Liquid Slugs in Inclined Tubes

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Abstract

This article studies rising velocity of Taylor bubbles and liquid slugs in liquid nitrogen at different axial positions in upward inclined tubes by means of a high speed motion analyzer. The bottom-closed tubes in the experiments are 1.0 m long with an inner diameter of 0.014 m or 0.018 m. The tube inclines upward from 0° to 50° with respect to the normal. Statistical method is used to analyze the data of the Taylor bubble and the liquid slug velocity. Reflecting the effects of the inclination angle on the rising velocity of Taylor bubbles and liquid slugs, the experimental results indicate the similar trend the Taylor bubble velocity and the liquid slug velocity have: it increases first, and then decreases with the increase of the inclination angle. Moreover, with the increase of the inclination angle, the liquid slug velocity becomes greater than Taylor bubble velocity.

Keywords: cryogenic two-phase flow; rising velocity; high speed motion analyzer; liquid nitrogen; Taylor bubble; liquid slug; inclined tube

1. Introduction

Gas-liquid two-phase slug flow is inherently unsteady and highly complicated. It is characterized by long bullet-shaped bubbles separated by liquid slugs that may teem with small dispersed bubbles. Slug flow has found wide applications in variety of industries inclusive of transportation and handling of cryogenic fluids.

With rapid development of aerospace technology, cryogenic propellants are broadly used in rockets. In cryogenic engineering, the heat leak, the common phenomenon in conveyor and storage system of cryogenic liquid, unavoidably gives birth to cryogenic two-phase flow, which causes many troubles, such as pressure calculation, stable operation, stratification, geysers and eddies[1]. Phenomena pertinent to geysers could cause transient pressure surges and high vapor flow rates that sometimes might be large enough to damage equipment. They pose new problems to the application of multi-phase flow theory in the cryogenic engineering. Therefore, ever-increasing rising velocity of Taylor bubbles and liquid slugs in upward inclined conveying pipes becomes an important issue in cryogenic two-phase flow.

In many industrial applications, gas bubbles are trapped within an enclosed channel such as a cylindrical tube. If the ratio of the bubble diameter, d, to the tube inner diameter, D, be greater than 0.6, the tube diameter becomes the controlling length that dominates the velocity and frontal shape of gas bubbles[2]. Bubbles of this type are called Taylor bubbles and tend to be bullet-shaped. Between two consecutive Taylor bubbles, there is an abundance of liquid with small dispersed bubbles. This region is termed liquid slug. Taylor bubbles, therefore, occupy most of the cross-section of the tube. The surrounding liquid flows around the moving bubbles in the form of a thin film. A Taylor bubble is composed of two distinctive parts: a rounded nose and a cylindrical body surrounded by a thin liquid film. Should the length of the slug be more than $1.5D$, the bubble velocity is independent of the Taylor bubble length. A Taylor bubble without fixed length in a vertical or inclined tube is still regarded as a Taylor bubble. In this case, the Taylor bubble velocity depends upon the tube diameter, inclination angle, θ, and the physical properties (density, viscosity, and surface tension) of the liquid.

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Bubble rise in stagnant fluid has long been an interested subject for extensive study and so far numerous publications can be found in the technical literature. In his early study, A. H. Gibson [3] discovered that bubble rise depends on the size of the bubble itself and the size relative to that of the tube. G. Barr[4] investigated the effects of bubble size, tube size, and viscosity on the bubble velocity. D. T. Dumitrescu [5] proposed the following Eq.(1) to calculate the drift velocity, U_d, of a single Taylor bubble in stagnant liquid, when the surface tension $\sum 4\sigma/(\Delta\rho g D^2) < 0.001$, where σ is the surface tension, $\Delta\rho$ the density difference between liquid and gas phases, g the gravitational constant.

$$U_d = 0.35\sqrt{gD} \tag{1}$$

R. M. Davies, et al. [6] provided a theoretical foundation to study bubbles in vertical tubes. Based on the assumed potential flow, they concluded that the Froude number (Fr) could be a constant in a vertical tube. Other important studies about bubble rise in vertical tubes were carried out by F. P. Betterton[7], H. L. Goldsmith, et al.[8], E. T. White, et al.[9], and R. A. S. Brown[10] and et al.

Bubble motion in inclined tubes has been studied by some researchers. E. T. White, et al.[9] noticed the influences of inclination angle on bubble rising velocity. E. E. Zukoski[11] studied the influences of inclination angle, viscosity and surface tension on the rising velocity. Bubble motion in inclined tubes inclusive of vertical and horizontal ones has also been studied by other researchers, such as C. C. Maneri, et al.[12], K. H. Bendiksen[13], M. E. Weber, et al.[14], B. Crouet, et al.[15], I. N. Alves, et al.[16] and R. van Hout, et al.[17-18]. All of them have revealed that the bubble velocity first increases and then decreases as the inclination angle increases.

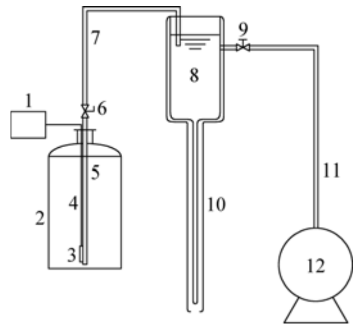
From the aforesaid review of the references concerning bubble rise in tubes, it is clear that most of the previous work has been devoted to the bubble motion in atmospheric temperature and in vertical tubes. For the Taylor bubble velocity and liquid slug velocity in cryogenic fluids in inclined tubes, could hardly be found any available reliable data.

The present study is meant to perform experimental investigation on the Taylor bubble velocity and liquid slug velocity in bottom-closed inclined tubes with liquid nitrogen as the work medium.

2. Description of Experiment

2.1. Experimental apparatus

Fig.1 shows the sketch of the experimental apparatus, which consists of a liquid nitrogen Dewar bottle, a test part and a vacuum pump as main components. The test part is made of double-layered Pyrex glass, which includes an upper tank and a cryogenic conveying tube (test section). The upper tank is 0.4 m long with an inner diameter of 0.1 m. The experimental tubes are 1.0 m long with inner diameters of 0.014 m and 0.018 m. The double-layered Pyrex glass can be rotated around its axis and fixed at one of inclination angles ranging from 0° to 50° with respect to the normal. Vacuumized by a vacuum pump to 6×10^{-2} Pa, the vacuum interlayer, 0.021 m clearance, functions as a thermal insulation to decrease the convection loss of heat.



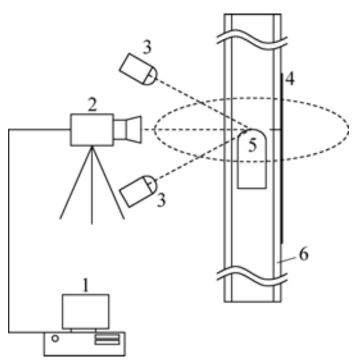
1—Power supply; 2—Liquid nitrogen Dewar bottle; 3—Electric heating rod; 4—Power cord; 5—Liquid nitrogen delivery tube; 6—Ball valve; 7—Flexible tube; 8—Upper tank; 9—Vacuum valve; 10—Test section; 11—Vacuum tube; 12—Vacuum pump

Fig.1 Experimental apparatus.

Stored in a Dewar bottle, the liquid nitrogen heated by an electric heating rod is supplied to the test section with the help of high-pressure nitrogen gas in the Dewar bottle. The liquid level of the upper tank is controlled between 1.16 m and 1.18 m to ensure the tube to be full of liquid nitrogen. Controlled by a power switch, the heating is stopped when the liquid level in the upper tank reaches about 1.18 m, and started when the level approaches 1.16 m.

2.2. Image processing system

Fig.2 shows the sketch of the image processing system, which is composed of a highspeed motion analyzer, a monitor, a light source and a computer. The highspeed motion analyzer (REDLAKE Motion-Pro®X3, 1 280×1 024 pixels resolution, 1 000 frame/s with the full resolution) is used together with a lens (AI NIKKOR 50/F1.2S) in the experiment, where the pixels resolution is 512×512, and the frame rate 1 000



1—Computer; 2—Highspeed motion analyzer; 3—Light; 4—Screen; 5—Taylor bubble; 6—Vacuum interlayer

Fig.2 A sketch of image processing system.

frame/s. The recorded images are transmitted to the computer for further analysis. Two photoflood lamps are used as light source with total power of 2 000 W.

2.3. Experimental condition

In the process of the experiment, the inclination angle was adjusted in the range of 0°-50°. The positions, x, of 20D-70D from the bottom of the tube with an inner diameter of 0.014 m and the positions of 20D-55D from the bottom of the tube with an inner diameter of 0.018 m were separately measured by using the high-speed motion analyzer.

2.4. Image processing

Fig.3 shows the determination of the Taylor bubble velocity, and Fig.4 the liquid slug velocity through image processing.

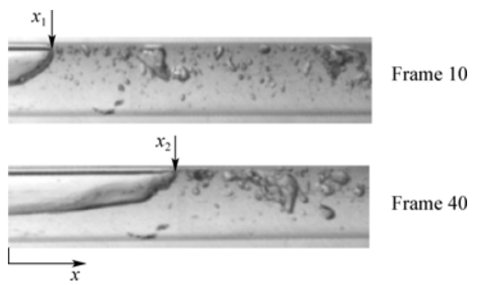


Fig.3 Determination of Taylor bubble velocity through image processing (D = 0.018 m, θ = 45°, frame number: 10 and 40, f =1 000 frame/s).

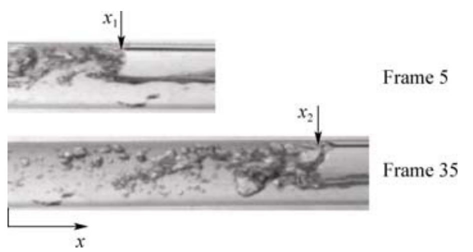


Fig.4 Determination of liquid slug velocity through image processing. (D = 0.018 m, θ = 45º, frame number: 5 and 35, f =1 000 frame/s).

The local propagation bubble velocity of the bubble interface is calculated as the shift of the pertinent interface divided by the time elapsed between two different-numbered frames:

$$U_{\mathrm{NTB}} = \frac{x_2 - x_1}{n\Delta t} \tag{2}$$

where U_{NTB} is the Taylor bubble velocity, x_1 the bubble nose position of Frame n_1 (see Fig.3), x_2 the nose position of Frame n_2 (also see Fig.3). From Figs.3-4, $n = n_2 - n_1$, $\Delta t = 1/f$, f is frame rate

The local propagation slug velocity is also calculated as the shift of the pertinent interface divided by the time elapsed between two different-numbered frames:

$$U_{\mathrm{NLS}} = \frac{x_2 - x_1}{n\Delta t} \tag{3}$$

where U_{NLS} is the liquid slug velocity, x_1 the bubble tail position of Frame n_1 (see Fig.4), x_2 the bubble tail position of Frame n_2 (also see Fig.4).

3. Results and Discussion

3.1. Liquid slug and nitrogen Taylor bubble video-images along tubes with various inclination angles

Fig.5 shows the evolution of nitrogen Taylor bubbles along the tube with an inner diameter of 0.018 m and various inclination angles, and Fig.6 the same for liquid slugs.

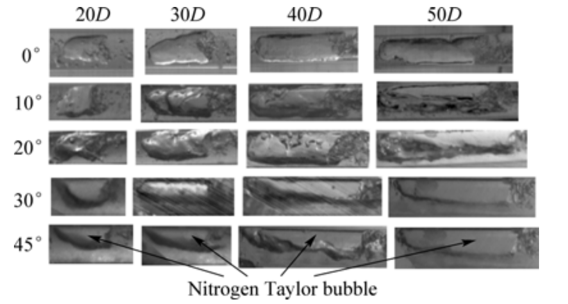


Fig.5 Nitrogen Taylor bubble image evolution along tube at various inclination angles D = 0.018 m.

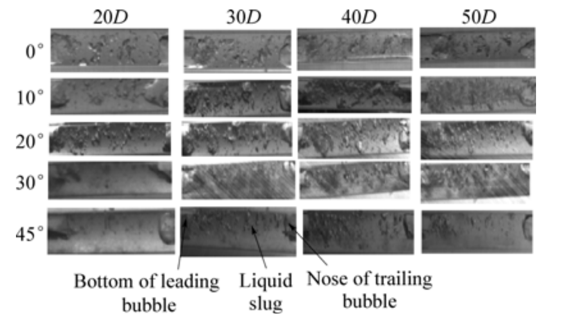


Fig.6 Liquid slug image evolution along tube at various inclination angles D = 0.018 m.

From Fig.5, it is obvious that the shape of the nitrogen Taylor bubbles undergoes significant change along the tube as the inclination angle changes, which means that all nitrogen Taylor bubbles are near the center of tube with 0°, 10° and 20° inclination, while they are near the upper wall of tubes with 30° and 45°. The nose of Taylor bubbles becomes distorted and sharper with the increase of θ. The left images in Fig.6 are the bottoms of the leading nitrogen Taylor bubbles, and the right the noses of the trailing nitrogen Taylor bubbles. Fig.6 indicates that enlarging θ would make small bubbles of liquid slug regions nearer to the tube upper wall.

3.2. Taylor bubble velocity along tubes with various inclination angles

Fig.7 presents the measured nitrogen Taylor bubble rising velocity as a function of position along the tube with an inner diameter of 0.014 m and various inclination angles, and Fig.8 the same along the tube with an inner diameter of 0.018 m. To facilitate the comparison of data from different experiments, the velocity is normalized by the velocity calculated by Eq.(1). Figs.7-8 indicate that near the tube exit, the rising velocity of Taylor bubble is almost constant at various inclination angles. Figs.7-8 show that when θ is 0°, 10° or 20°, the velocity increases along the tube with an inner diameter of 0.014 m. When $\theta = 30°$, it increases to the maximum at $x/D = 40$, and then decreases along the tube. When θ is 45° or 50°, the velocity decreases along the tube. In Figs.7-8, when θ is 0°, 10°, 20° or 30°, the results are different from those of undeveloped air-water slug flow[17-19]. This may possibly be attributed to the insufficient development of slug flow, the presence of dispersed bubbles in the liquid slug region and the refilling of the tube by the liquid from upper tank as the liquid slug above the region of the nitrogen Taylor bubble is forced out of the tube at a certain speed. When θ is 45° or 50°, the results are similar with those of undeveloped air-water slug flow. This might be sourced back to the inclination angles. When the inclination angle is large enough, the effects of the refilling by the liquid from upper tank become too weak to affect the velocity.

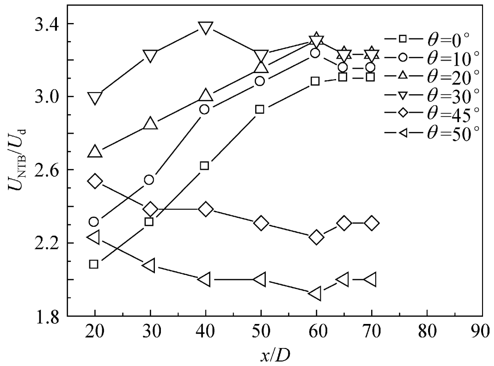


Fig.7 Taylor bubble velocity along tube with various inclination angles ($D = 0.014$ m).

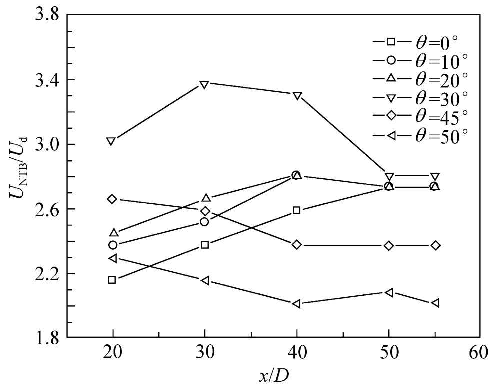


Fig.8 Taylor bubble velocity along tube with various inclination angles ($D = 0.018$ m).

Figs.7-8 also show that at different positions along the tube with an inner diameter of 0.014 m, the velocity increases first, and then decreases with increase of θ. The same is true of the tube with an inner diameter of 0.018 m excepting at the exit of the tube. The results from both tubes are consistent with those from inclined tubes[12-16]. When $\theta = 30°$, the velocity reaches the maximum at various positions along the tube. The possible reason for this is the changes of the force condition of the Taylor bubbles. Fig.5 clearly shows that increasing θ changes the lateral position of Taylor bubble, and distorts its nose, which in turn leads to the reduction of resistance. As a result, the Taylor bubble velocity increases with θ increasing. When $\theta > 30°$, the rapid increase of friction-induced drag force would decrease the Taylor bubble velocity. At the exit of the tube with an inner diameter of 0.018 m, the velocity decreases with the increase of θ as distinct from what happens in the inclined tubes.

Figs.9-10 show the standard deviation (S.D.) of nitrogen Taylor bubble rising velocity in the two different-sized inclined tubes. From both figures, it is noted that the standard deviation is always under 0.13. When $\theta < 30°$, the standard deviation is less than that for the two tubes with larger inclination angles. This indicates a more stable flow condition in the cases with small inclination angles. Both figures also show minor variation in rising velocity between Taylor bubbles.

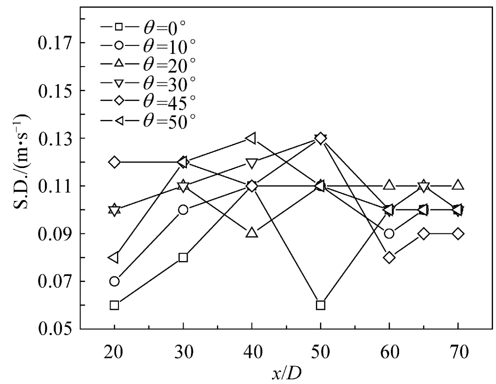


Fig.9 Standard deviation of nitrogen Taylor bubble rising velocity in an inclined tube ($D = 0.014$ m).

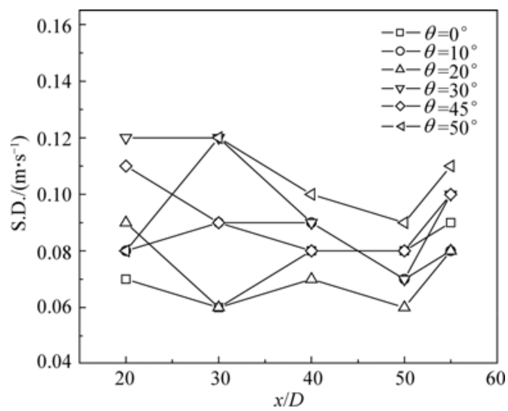


Fig.10 Standard deviation of nitrogen Taylor bubble rising velocity in an inclined tube ($D = 0.018$ m).

3.3. *Liquid slug velocity along tubes with various inclination angles*

Figs.11-12 present the measured nitrogen liquid slug rising velocity as a function of position along the two different-sized tubes with various inclination angles.

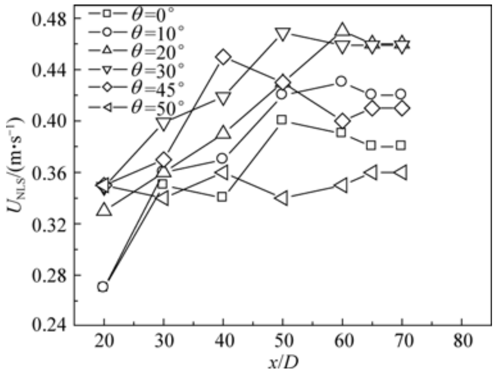


Fig.11 Liquid slug velocity along tube with various inclination angles (D=0.014 m).

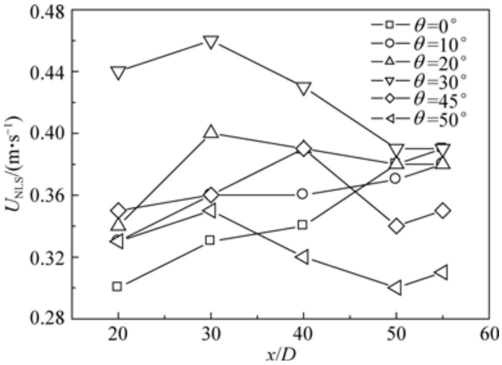


Fig.12 Liquid slug velocity along tube with various inclination angles (D = 0.018 m).

Figs.11-12 indicate that near the tube exit, the liquid slug rising velocity remains almost constant in the tubes with various inclination angles. Fig.11 shows that when θ is 0°, 10°, 20° or 30°, the velocity increases along the tube with an inner diameter of 0.014 m. When $\theta = 45°$, the velocity increases first, and then decreases along the tube with the peak at $x/D = 40$. When $\theta = 50°$, the velocity almost keeps unchanged along the tube. Fig.12 shows that when θ is 0° or 10°, the velocity increases along the tube with an inner diameter of 0.018 m. When θ is 20°, 30°, 45° or 50°, the velocity increases first and then decreases along the tube. When θ is 20°, 30° or 50°, the velocity reaches the maximum at $x/D = 30$. However, when $\theta = 45°$, the velocity reaches the maximum at $x/D = 40$.

Figs.11-12 also show that at different positions along the tube with an inner diameter of 0.014 m, the velocity increases first and then decreases with the increase of θ at different positions along the tube, while the maximum of velocity always occurrs at $\theta = 20^{\circ}$ or $\theta = 30^{\circ}$. With $\theta = 45^{\circ}$, the maximum of velocity occurs at $x/D = 40$. For the tube with an inner diameter of 0.018 m, the velocity increases first and then decreases along the tube with the θ increasing. When $\theta = 30^{\circ}$, the velocity reaches the maximum at various positions along the tube.

Figs.13-14 list the standard deviation of the nitrogen liquid slug rising velocity in the inclined tubes. It should be noted that the standard deviation of U_{NLS} can approach about 0.13 m/s or so, which indicates small variation between individual slugs.

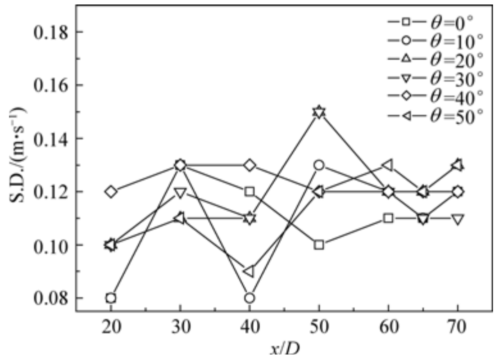


Fig.13 Standard deviation of nitrogen liquid slug rising velocity in an inclined tube (D = 0.014m).

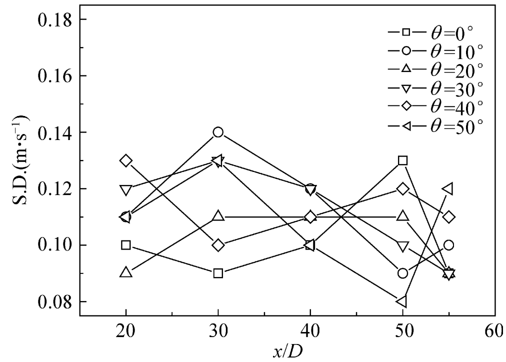


Fig.14 Standard deviation of nitrogen liquid slug rising velocity in an inclined tube (D = 0.018 m).

3.4. Comparison of Taylor bubble and liquid slug velocities along tubes with various inclination angles

Table 1 shows the values of U_{NTB} and U_{NLS} measured independently at the position of 40D of the tubes with various inclination angles. Under the boiling flow condition, the expansion of Taylor bubbles should be taken into consideration. The experimental data indicate that in the tube with an inner diameter of 0.014 m, when $\theta < 30^{\circ}$, the liquid slug velocity is almost the same as the Taylor bubble velocity; when $\theta > 30^{\circ}$, the liquid slug velocity is obviously greater than the Taylor bubble velocity. In the tube with an inner diameter of 0.018 m, the liquid slug velocity is almost the same as the Taylor bubble velocity in tubes with various inclination angles. Once $\theta > 30^{\circ}$, U_{NLS} is always higher than U_{NTB} by several percents.

Table 1 Taylor bubble and liquid slug velocities along tubes with various inclination angles (x/D = 40)

θ/(°)	D=0.014 m		D=0.018 m	
	U_{NTB}/(m·s^{-1})	U_{NLS}/(m·s^{-1})	U_{NTB}/(m·s^{-1})	U_{NLS}/(m·s^{-1})
0	0.34	0.34	0.36	0.34
10	0.38	0.37	0.39	0.36
20	0.39	0.39	0.39	0.39
30	0.44	0.42	0.46	0.43
45	0.31	0.45	0.33	0.39
50	0.26	0.36	0.28	0.32

4. Conclusions

This article presents an experimental study on the evolution of continuous liquid nitrogen boiling flow along inclined tubes with inner diameters of 0.014 m and 0.018 m. The hydrodynamic and statistical parameters under study include nitrogen Taylor bubble velocity and liquid slug velocity. The measurements are made with high speed motion analyzer at different positions along the tube.

The results are introduced as follows:

Through image analyzing, the whole nitrogen Taylor bubble region is found to be near the center of tubes with inclination angles of 0º, 10º and 20º, while near the upper wall of tubes with 30º and 45º. The small liquid slug bubbles are near the upper wall of tubes and the smaller the angle, the nearer the bubbles. The noses of Taylor bubble become distorted and sharper as θ increases and the larger the θ, the more serious the distortion and sharpness.

When the inclination angle is 0°, 10° or 20°, the mean nitrogen Taylor bubble velocity increases along the tubes. When θ = 30°, the velocity increases first, and then decreases along the tube; when θ is 45° or 50°, it decreases.

At the same position, the Taylor bubble velocity increases first, and then decreases with the inclination angle increasing. When θ = 30°, the mean Taylor bubble velocity reaches the maximum at all the positions along the tubes. At the exits of tubes, the nitrogen Taylor bubble velocity turns stable despite of different inclination angles.

The effects of the inclination angle on the liquid slug velocity vary with different-oriented tubes. At the same position, the liquid slug velocity increases first, and then decreases with the inclination angle increasing. The maximum of velocity always occurs at θ = 20º or 30º. At the exits of the tubes, the nitrogen liquid slug velocity turns stable no matter what inclination angle the tube has.

Comparison between the Taylor bubble velocity and liquid slug velocity tells us that when θ < 30º, the liquid slug velocity is almost the same as the Taylor bubble velocity and once θ >30º, U_{NLS} is always higher than U_{NTB}.

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Biography:

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